Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: National Taiwan University 802.15.7r1 OCC Proposal

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Re: CFP Response

Abstract: CFP Response

National Taiwan University 802.15.7r1 OCC Proposal

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REQUIREMENTS

Transmitter Requirements

Overall objective:
Retain the transmitter's original function

- The transmission should not create **flickers** visible to human eyes
- The transmitting LED should still retain **dimming** capability
- Use only **ON and OFF** – binary levels to modulate data (simple transmitter design, minimum modifications to existing systems, cost efficient)
- **Color** is not used to modulate data (color is determined by user preference)

Receiver Requirements

Overall Objective: Use existing hardware

- Use off-the-shelf, **unmodified** rolling shutter camera as the receiver
  - Adding software (e.g. smartphone app) instantly gives existing devices the reception capability
  - The start of the exposure duration is assumed NOT controllable (**unsynchronized** channel)
  - Camera frame rate is **NOT accurate** and can **vary** over time

Receiver Requirements

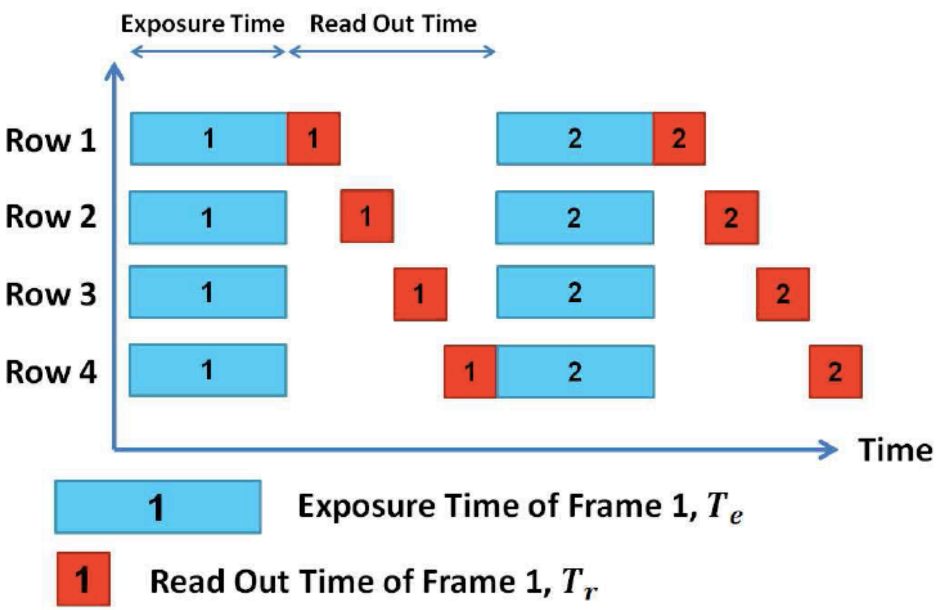
- Cameras using **different image sensors** should be able to demodulate **the same transmission** simultaneously
  - Parameters that could be different include
    - Resolution
    - Row read-out duration
    - Frame rate
    - Exposure duration
    - TX-RX distance
- Camera receiver should be able to receive even when the transmitter does not occupy the entire image (operate at **longer distance** & in **line-of-sight** scenarios)

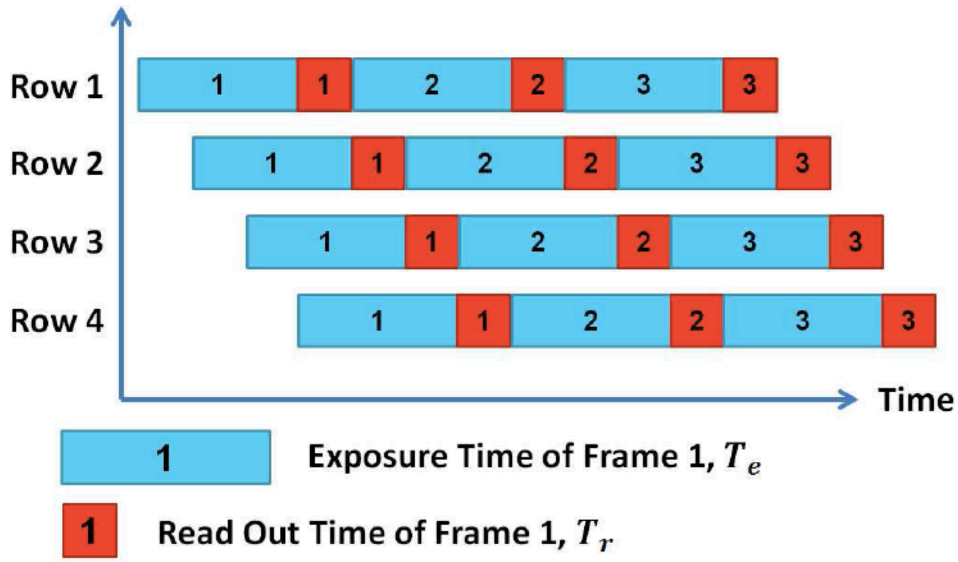
BACKGROUND

Light-to-Rolling-Shutter-Camera Channel

- Main characteristics:
  1. Rolling exposure process (rolling shutter sampling)
  2. Time gap
  3. Low-pass filtering due to integration during exposure

Global versus Rolling Shutter

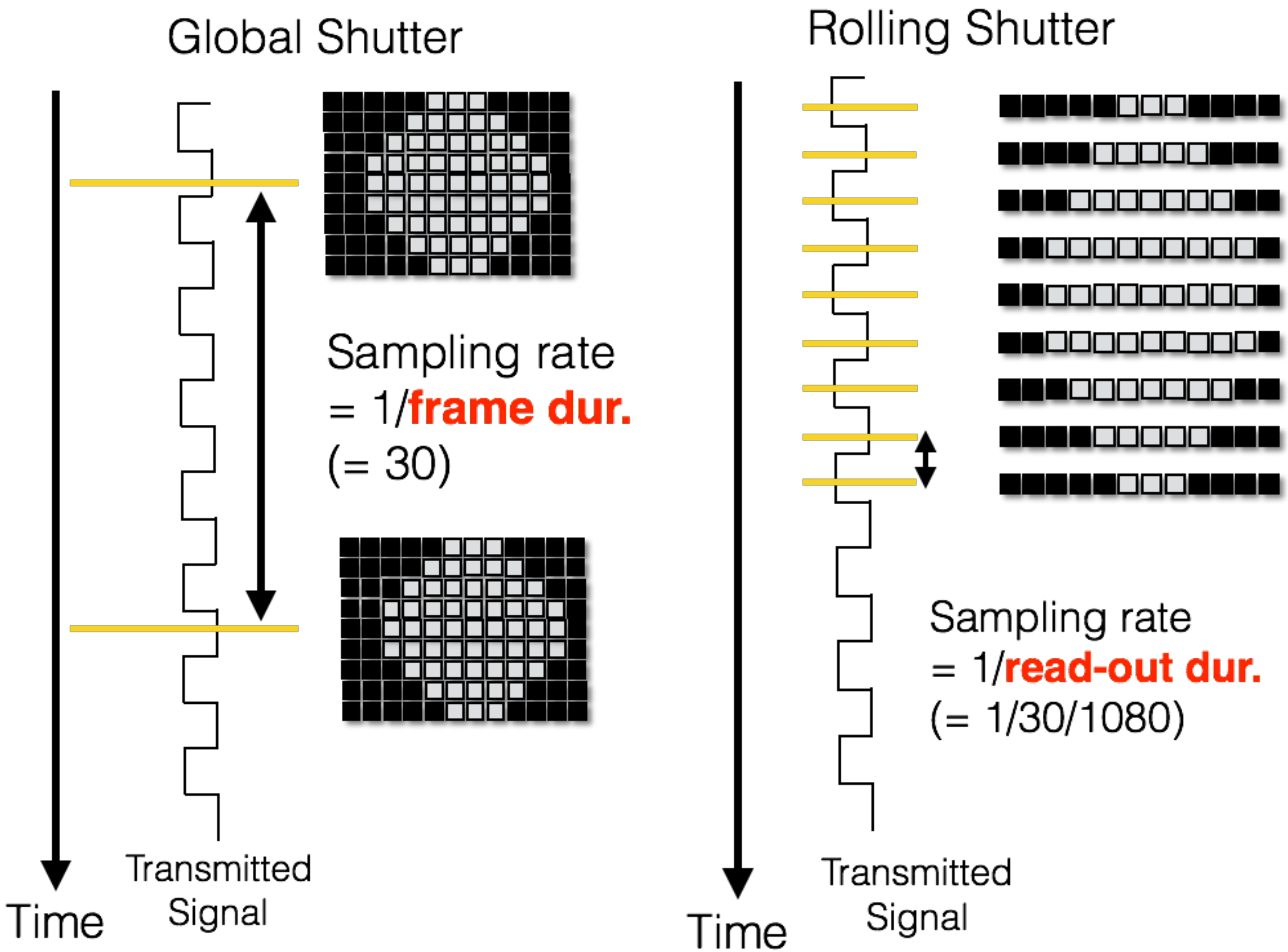




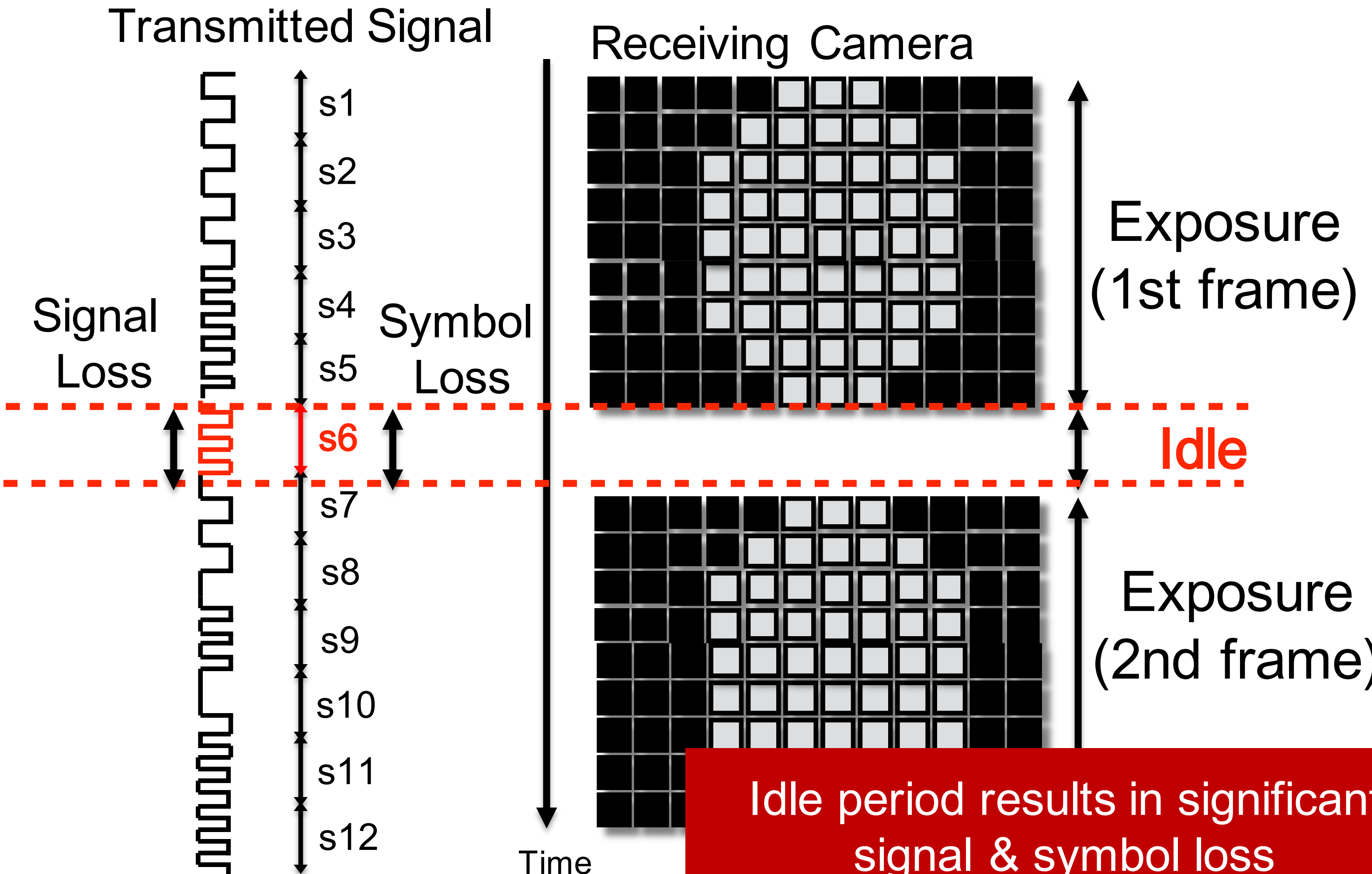
Global Shutter:
All pixels exposed
at the same time

Rolling Shutter:
Pixels are exposed
row by row

Comparison of Sampling Schemes

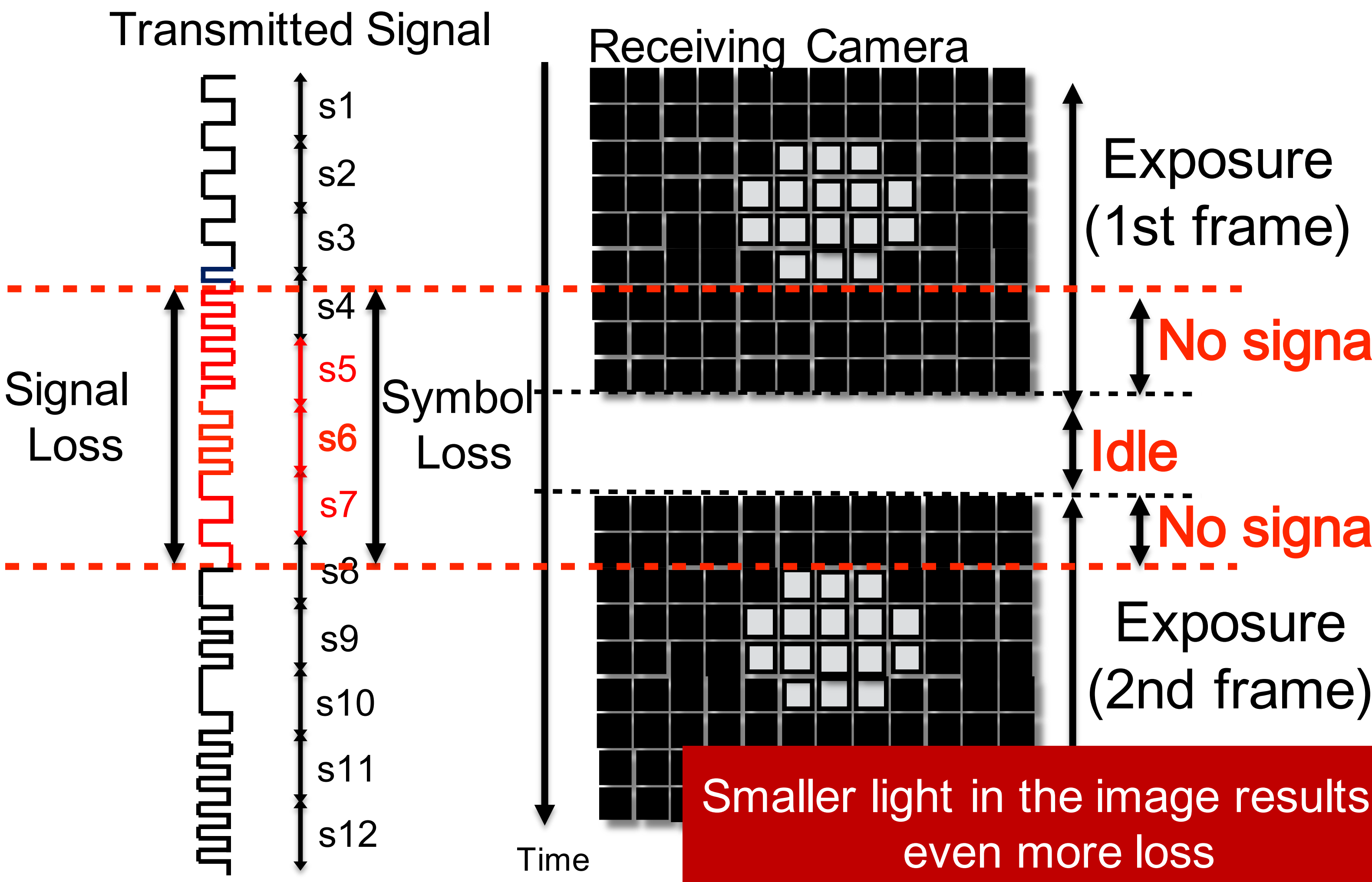


Idle Period



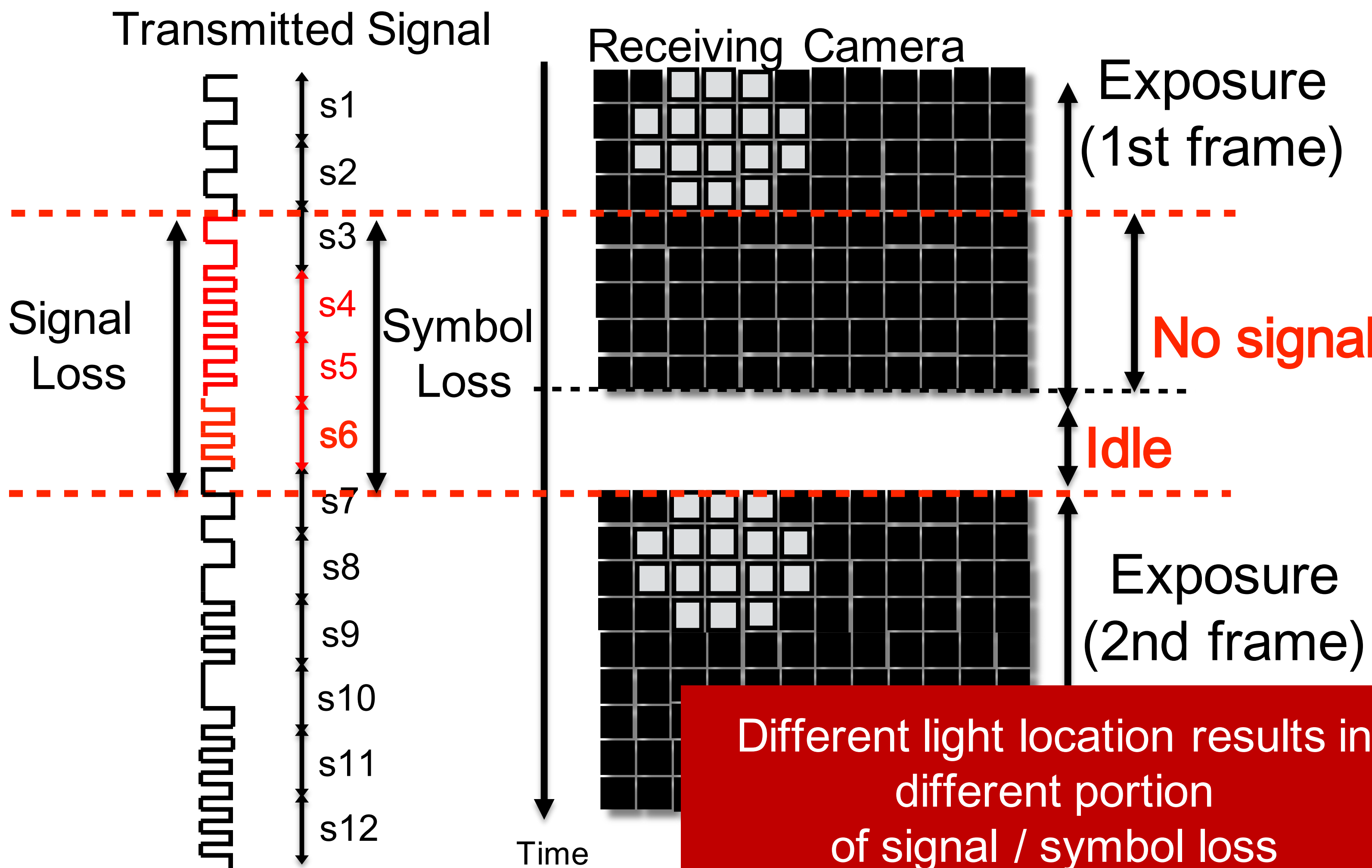
Idle period results in significant signal & symbol loss

Idle Period + Un-occupied Area



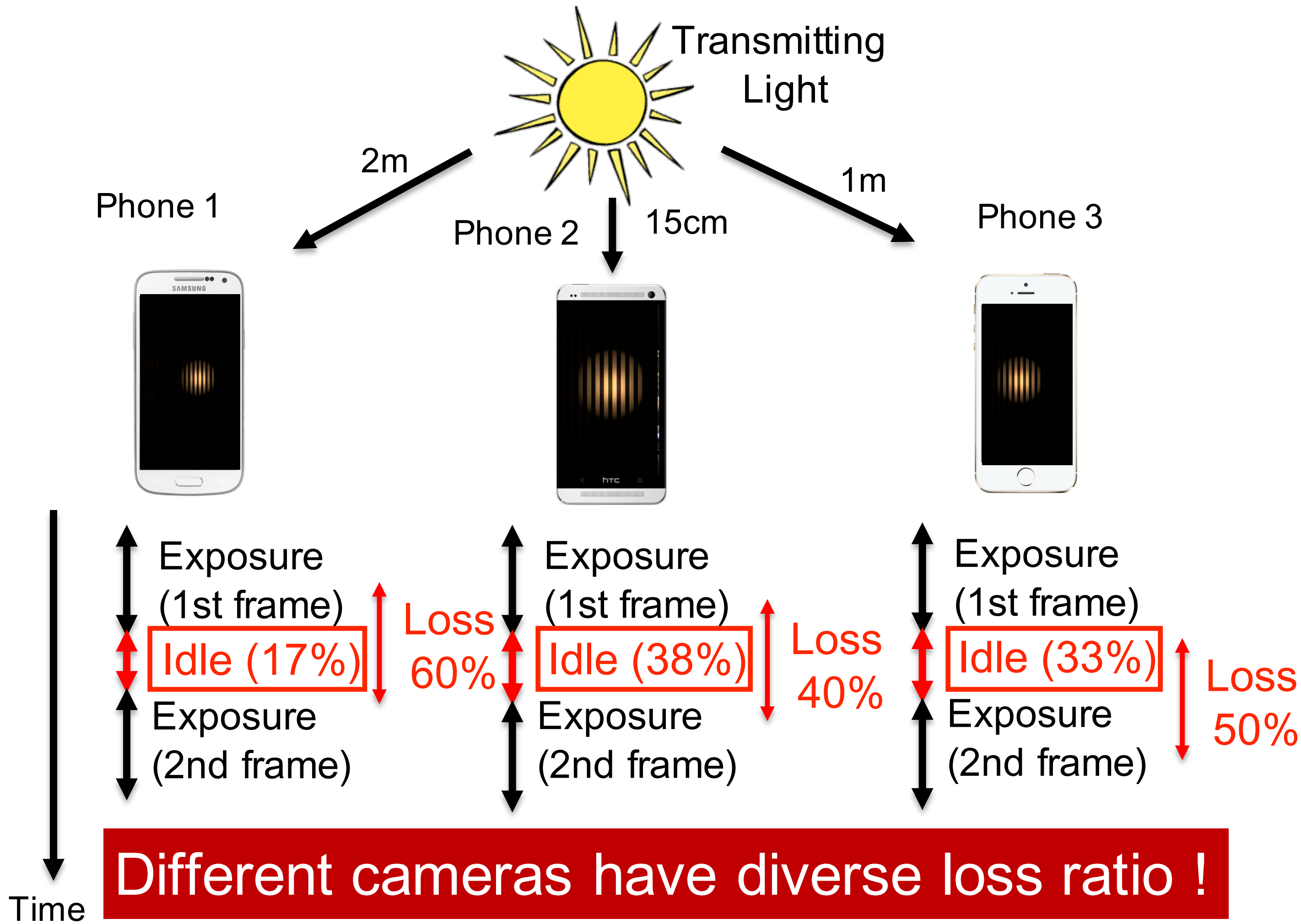
Smaller light in the image results in even more loss

Idle Period + Un-occupied Area



Different light location results in different portion of signal / symbol loss

Idle Period + Un-occupied Area = Time gap = Lossy Channel



Different cameras have diverse loss ratio !

Examples of Camera Parameters

	Image Resolution (X x Y)	Frame Rate (fps)	Measured Read-out Duration (μs)	Time Gap (ms) (Percentage of Frame Duration)
Apple iPhone 6 Plus	1920x1080	30	21.42	10.20 (30.60%)
Apple iPhone 5s	1920x1080	29.98	20.65	11.03 (33.10%)
Apple iPhone 4s	1920x1080	29.87	24.48	7.04 (21.03%)
HTC New One	1920x1080	29.94	19.08	12.79 (38.30%)
Samsung Galaxy S4	1920x1080	29.93	25.53	5.84 (17.48%)
Point Grey Flea3	2048x1080	30	14.73	17.42 (52.27%)

Low-pass Filtering due to Exposure

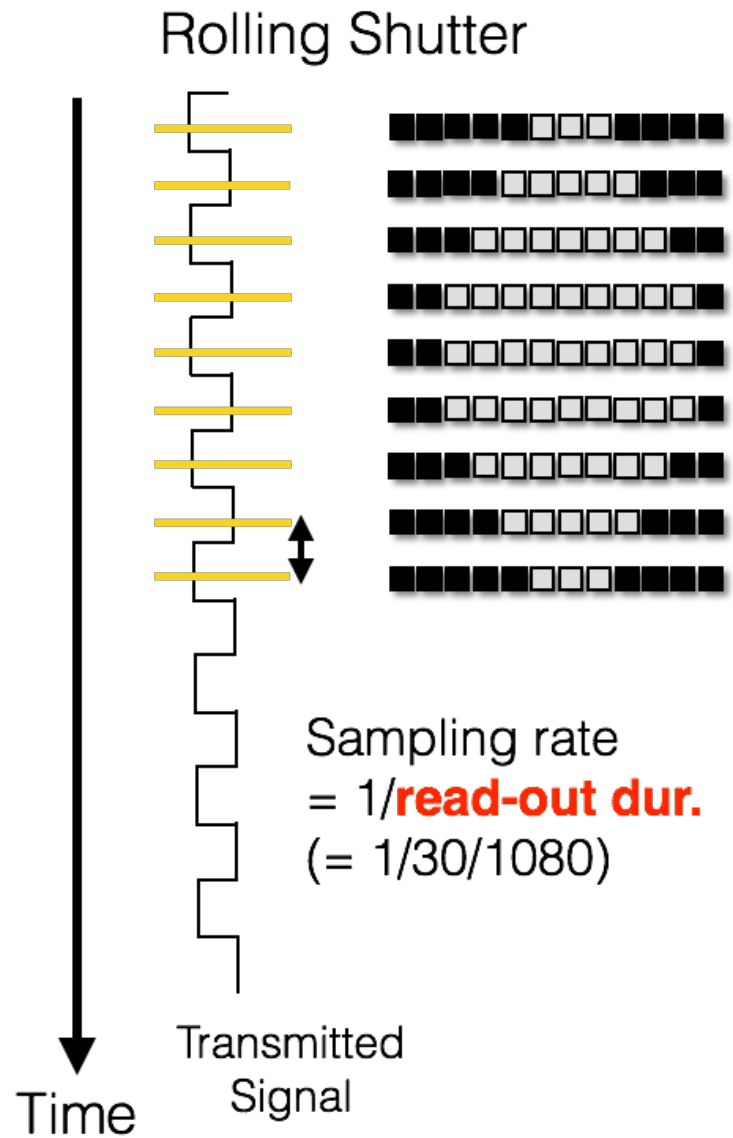
- Pixel intensity of y-th row of pixel(s):

$$I[y] = \int_{T_0+(y-1)T_r}^{T_0+(y-1)T_r+T_e} r(y,t)dt$$

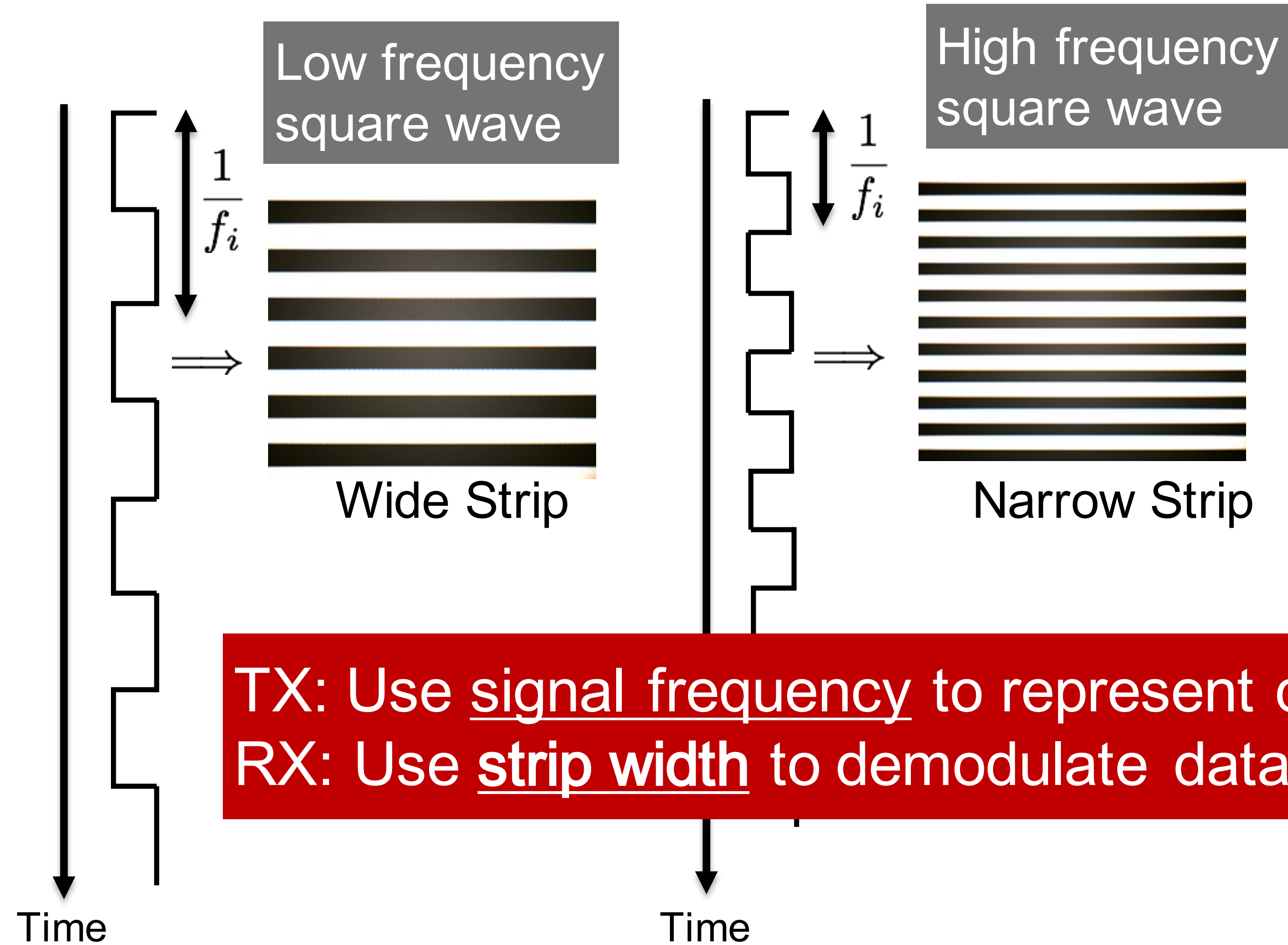
  - $r(y,t)$: received signal of the y-th row at time t
  - T_0: start of exposure for this image frame
  - T_e: exposure duration
  - T_r: row read-out duration
- Long T_e results in significant low-pass filtering!

PHY PROPOSAL - ROLLING-SHUTTER FREQUENCY SHIFT KEYING

Recap: Rolling Shutter Sampling

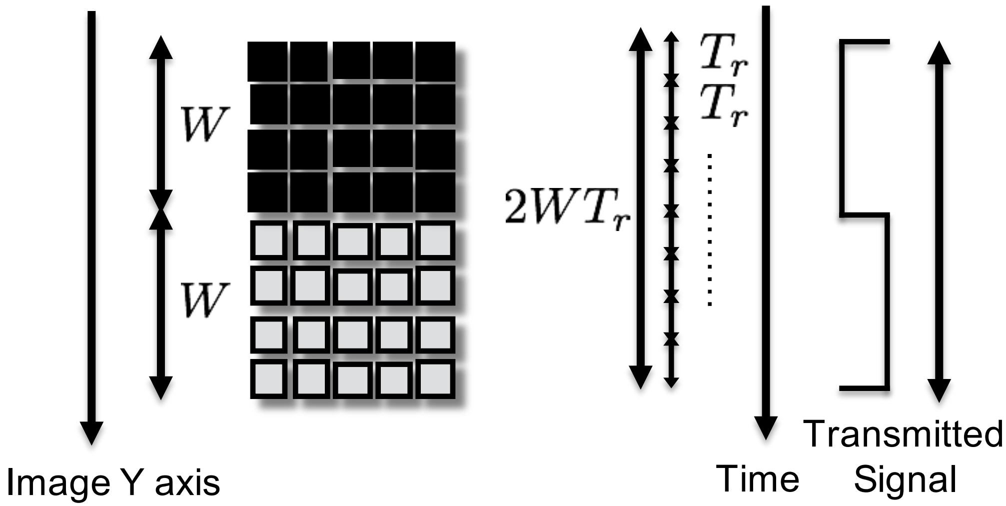


Rolling Shutter – Frequency Shift Keying (RS-FSK)



TX: Use signal frequency to represent data.
RX: Use **strip width** to demodulate data.

Relation between Frequency and Strip Width



$$2WT_r = \frac{1}{f_i}$$

$$\Longrightarrow f_i = \frac{1}{2WT_r}$$

T_r : read-out duration.

Transmitter

selects a frequency f_i from $\mathcal{F}$:

$$\mathcal{F} = \{f_1, f_2, ..., f_n\}$$

to represent $log_2|\mathcal{F}|$ bits.

Receiver

estimates f_i with

$$f_i = \frac{1}{2WT_r}$$

RS-FSK Advantages

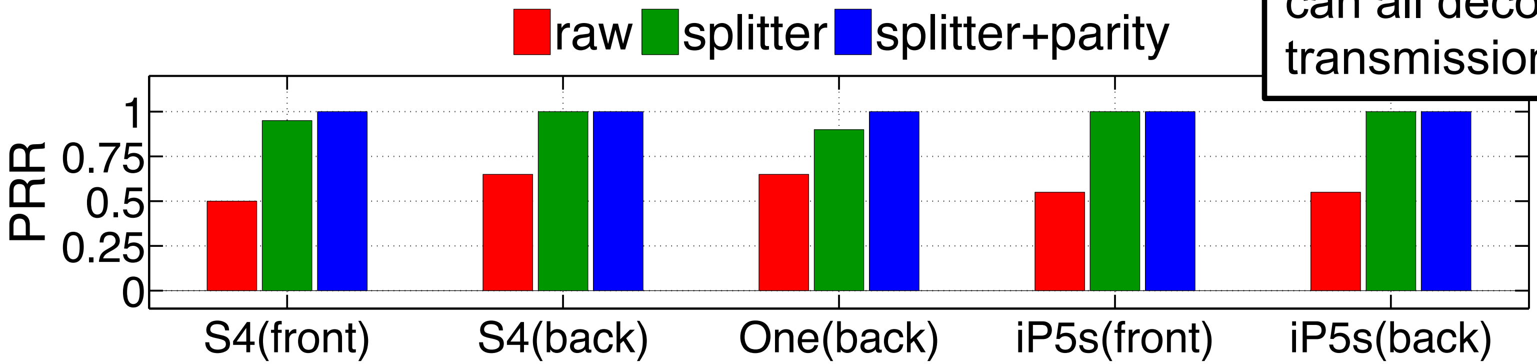
1. **Average intensity stays the same** for different symbols over one symbol period (avoid flickers)
2. The waveform can be demodulated by receivers with **different (rolling shutter) sampling rates** (i.e., read-out duration)
3. Demodulation is possible even when **partial symbol is lost** (cope with lossy channel)
4. **Low-pass filtering** does not destroy the signal as long as the exposure duration is not an integer multiples of the signal period
5. Dimming can be realized by changing the **duty cycle** of the signal

YIN - Accurate Frequency Estimation for RX

Advantages:

1. Time-domain autocorrelation handles variable signal length
2. Parabolic interpolation improves accuracy when W **is not an integer**
3. Measures to handle slow varying DC, i.e., non-uniform illumination surface

Experimental results show that all test cameras can all decode the same transmission!



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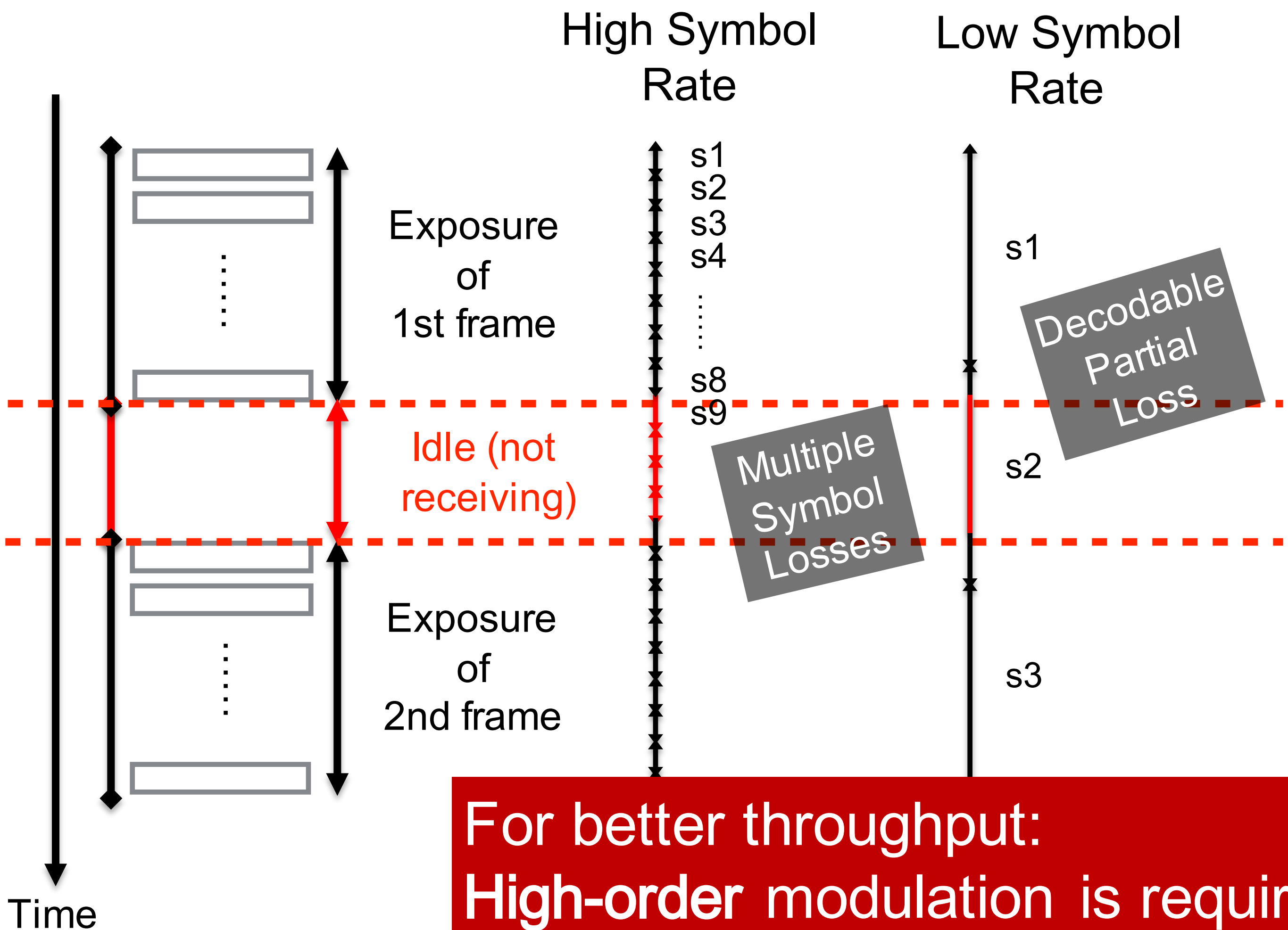
High-Order Modulation - Partial Symbol Loss



For better throughput:
High-order modulation is required!

RS-FSK Advantages

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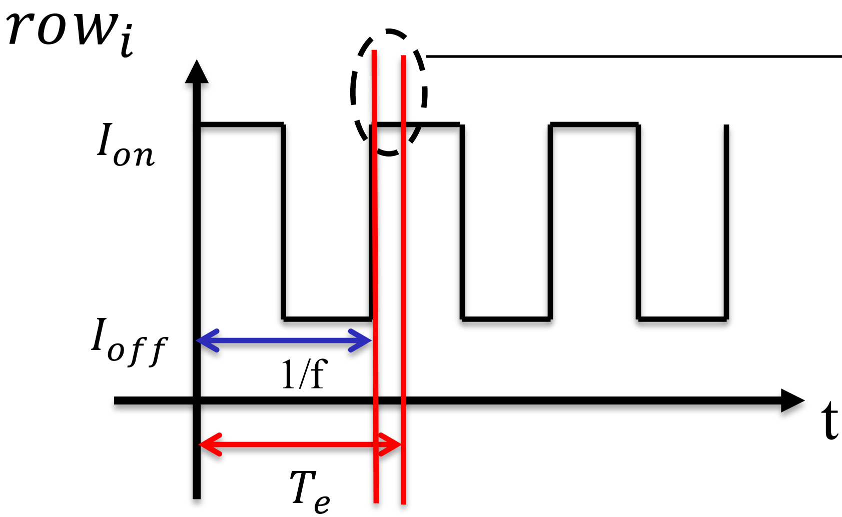
RS-FSK When Considering Exposure

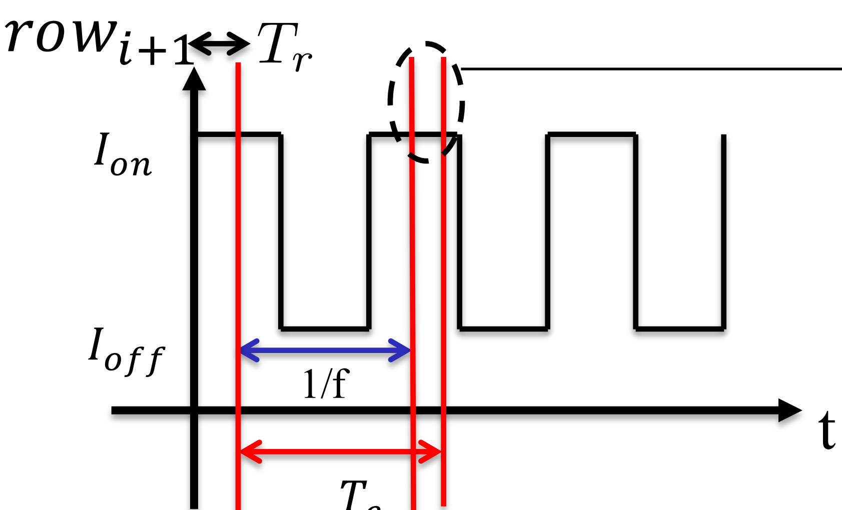


$$\int^{T_e} r(i,t)dt = \frac{I_{\text{on}} + I_{\text{off}}}{2} \cdot k \cdot \frac{1}{f} + I_{\text{on}}(T_e \mod \frac{1}{f})$$

Average intensity over k signal period

"variation": **bright!**

Actual captured image

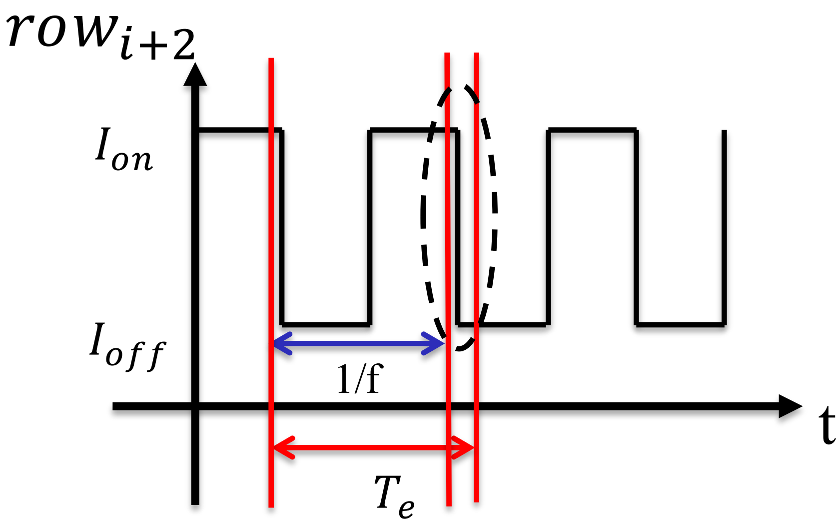


$$\int^{T_e} r(i+1,t)dt = \frac{I_{\text{on}} + I_{\text{off}}}{2} \cdot k \cdot \frac{1}{f} + I_{\text{on}}(T_e \mod \frac{1}{f})$$

Average intensity over k signal period

"variation": **bright!**

RS-FSK When Considering Exposure

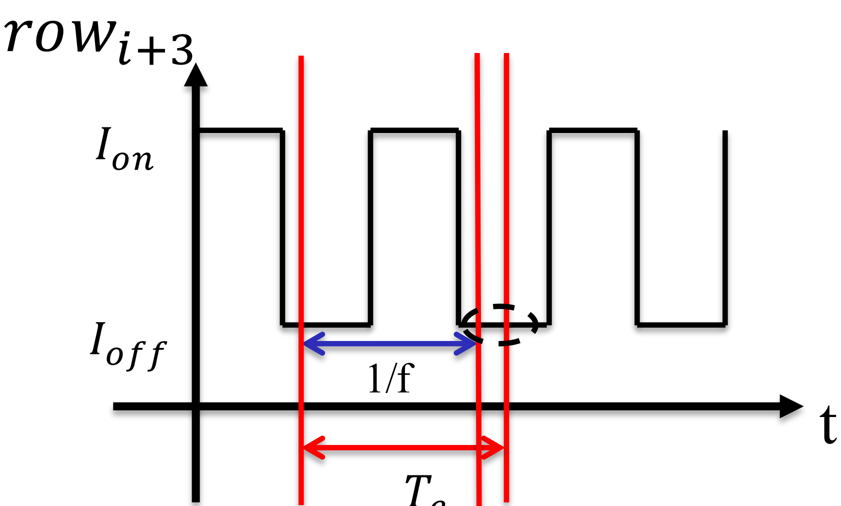


$$\int^{T_e} r(i+2,t)dt$$

$$= \frac{I_{on}+I_{off}}{2}\cdot k\cdot\frac{1}{f} + \{\alpha\cdot I_{on}+(1-\alpha)\cdot I_{off}\}(T_e \mod \frac{1}{f})$$

Average intensity over k signal period

"variation": **mixed**



$$\int^{T_e} r(i+3,t)dt$$

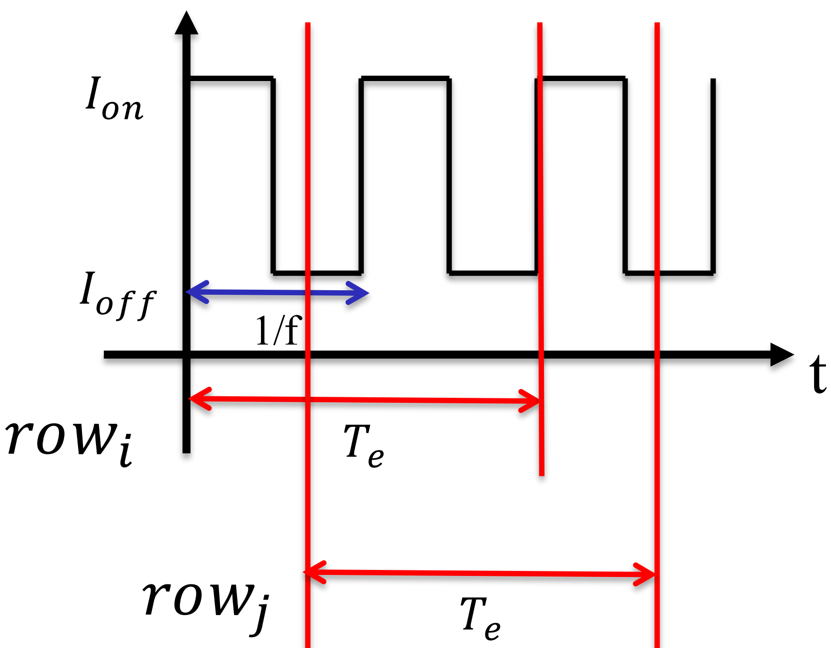
$$= \frac{I_{on}+I_{off}}{2}\cdot k\cdot\frac{1}{f} + I_{off}(T_e \mod \frac{1}{f})$$

Average intensity over k signal period

"variation": **dark**!

The Case Where RS-FSK is not Observed

When exposure is an integer multiple of the signal period



$$T_e = k \cdot \frac{1}{f} \quad \Rightarrow T_e \mod \frac{1}{f} = 0$$

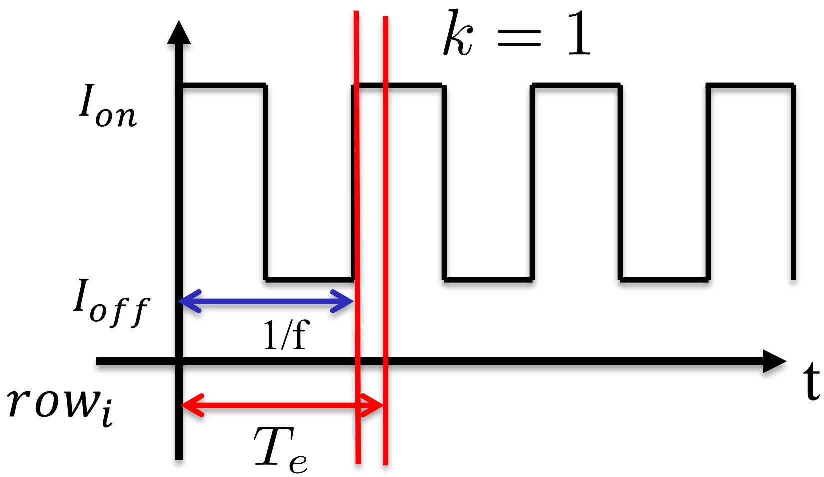
$$\int^{T_e} r(i,t)dt = \frac{I_{on} + I_{off}}{2} \cdot k \cdot \frac{1}{f} + I(T_e \mod \frac{1}{f}) \rightarrow 0$$

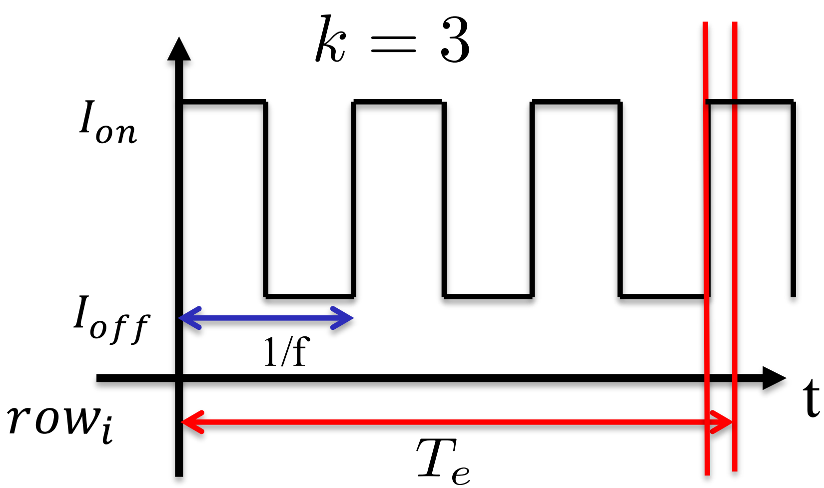
Average intensity over k signal period

The result stays the same for all rows!

No "variation"! No stripe pattern!

RS-FSK with Different Exposure Durations





$$T_e = k \cdot \frac{1}{f} + (T_e \mod \frac{1}{f})$$

$$\int^{T_e} r(i,t)dt = \frac{I_{\text{on}} + I_{\text{off}}}{2} \cdot \boxed{k \cdot \frac{1}{f}} + I\boxed{(T_e \mod \frac{1}{f})}$$

Average intensity over **k signal period**

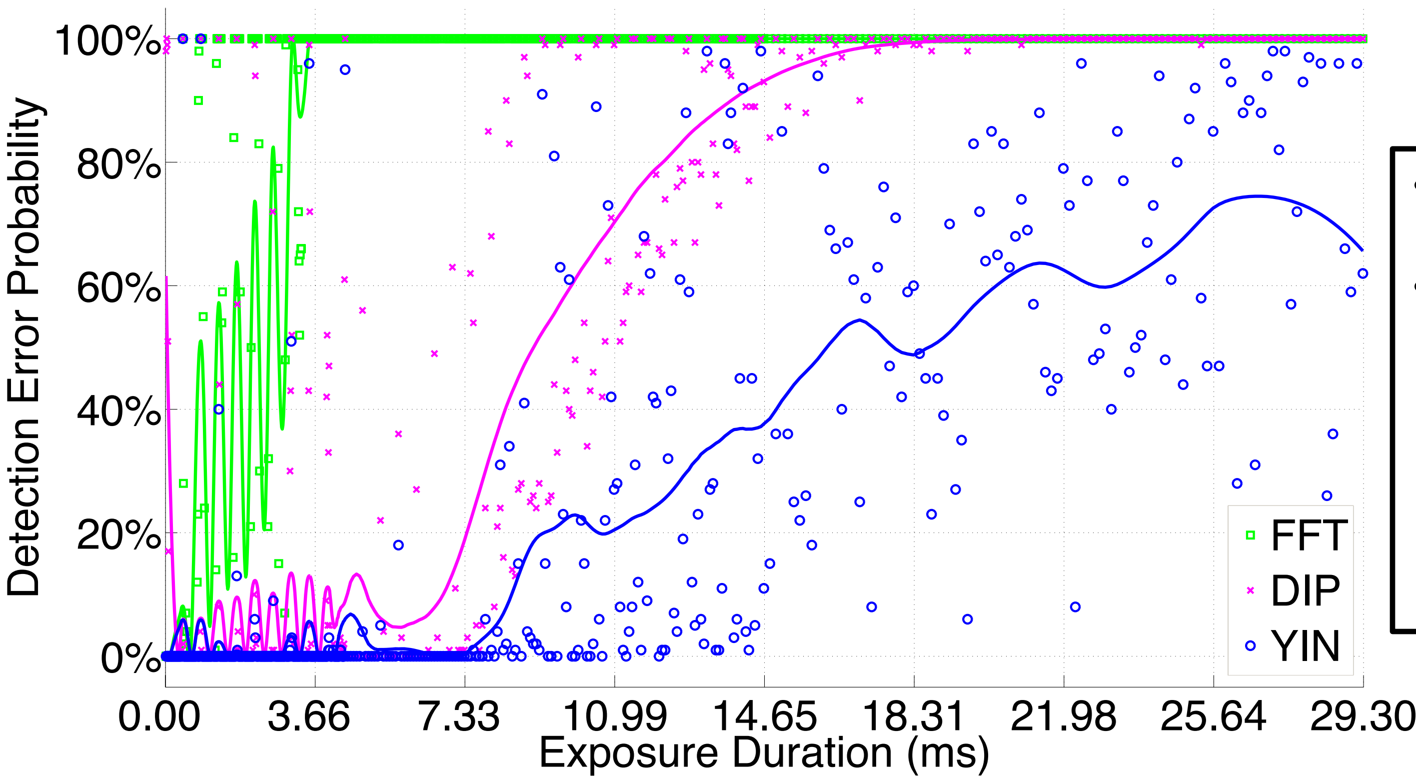
"Variation" over $\mathbf{T_e \mod \frac{1}{f}}$

As the exposure duration T_e increases, "variation" becomes small compared to the average intensity

RS-FSK with Exposure / Low-pass Filtering

1. In most cases, **with arbitrary exposure duration setting,** RS-FSK signal remains detectable in the received images.
   – The observed signal frequency in the images is the same as the transmitted signal frequency
2. When the exposure duration is (approximately) an integer multiple of the signal period, the signal is NOT detectable.
   – This can be regarded as **channel fading** for that signal frequency
3. As the exposure duration increases, the difference between bright and dark strips (ON/OFF states) becomes small.
   – When this difference becomes less than the intensity resolution of the image, the signal is no longer visible.

Validation with Experimental Results



- Tested with **3 flavors** of algorithms
- Each demodulation is regarded as erroneous if the estimated signal period is **off by more than one read-out duration**

Reasonable error probability up to tens of milliseconds

RS-FSK Advantages

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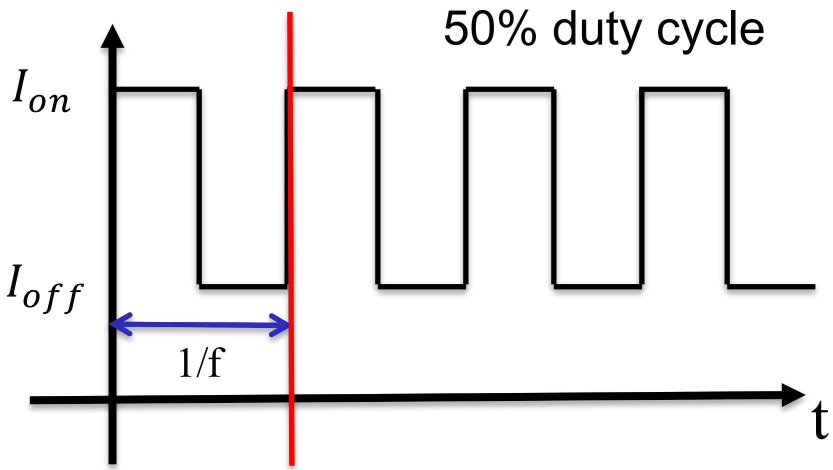
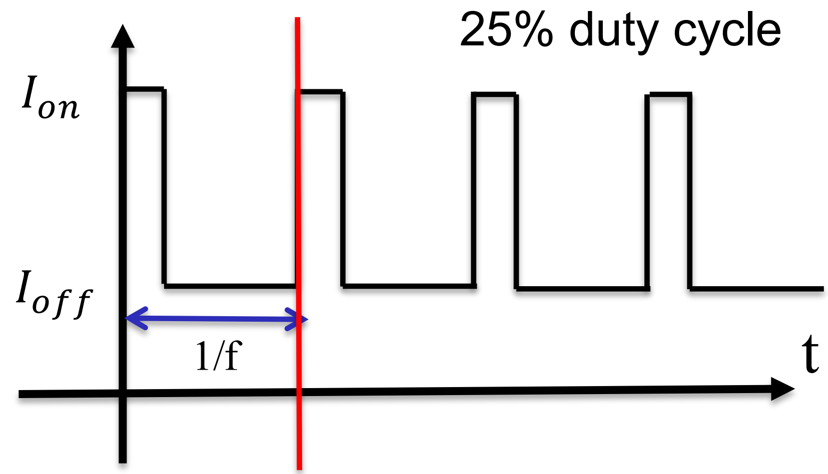
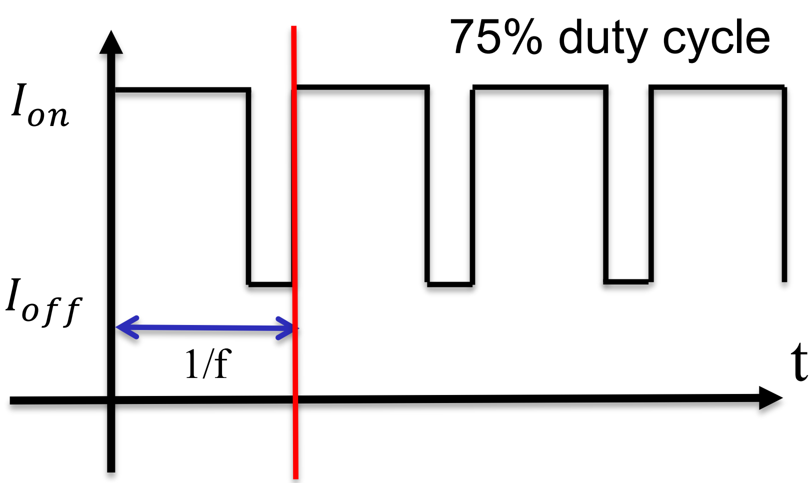
2. The waveform can be demodulated by receivers with **different (rolling shutter) sampling rates** (i.e., read-out duration)
3. Demodulation is possible even when **partial symbol is lost** (cope with lossy channel)
4. **Low-pass filtering** does not destroy the signal as long as the exposure duration is not an integer multiples of the signal period
5. Dimming can be realized by changing the **duty cycle** of the signal

Dimming with Duty Cycle







- Change square wave **duty cycle** to adjust observed brightness
- Duty cycle is **independent** of and **does not affect signal frequency *f***

MAC PROPOSAL – FRAME FOR RS-FSK

MAC Proposal

Main Objective: Compensate for significant signal loss and unsynchronized channel

Problems & Proposed Solutions:

1. Mis-aligned symbol boundary

   Symbol Splitter

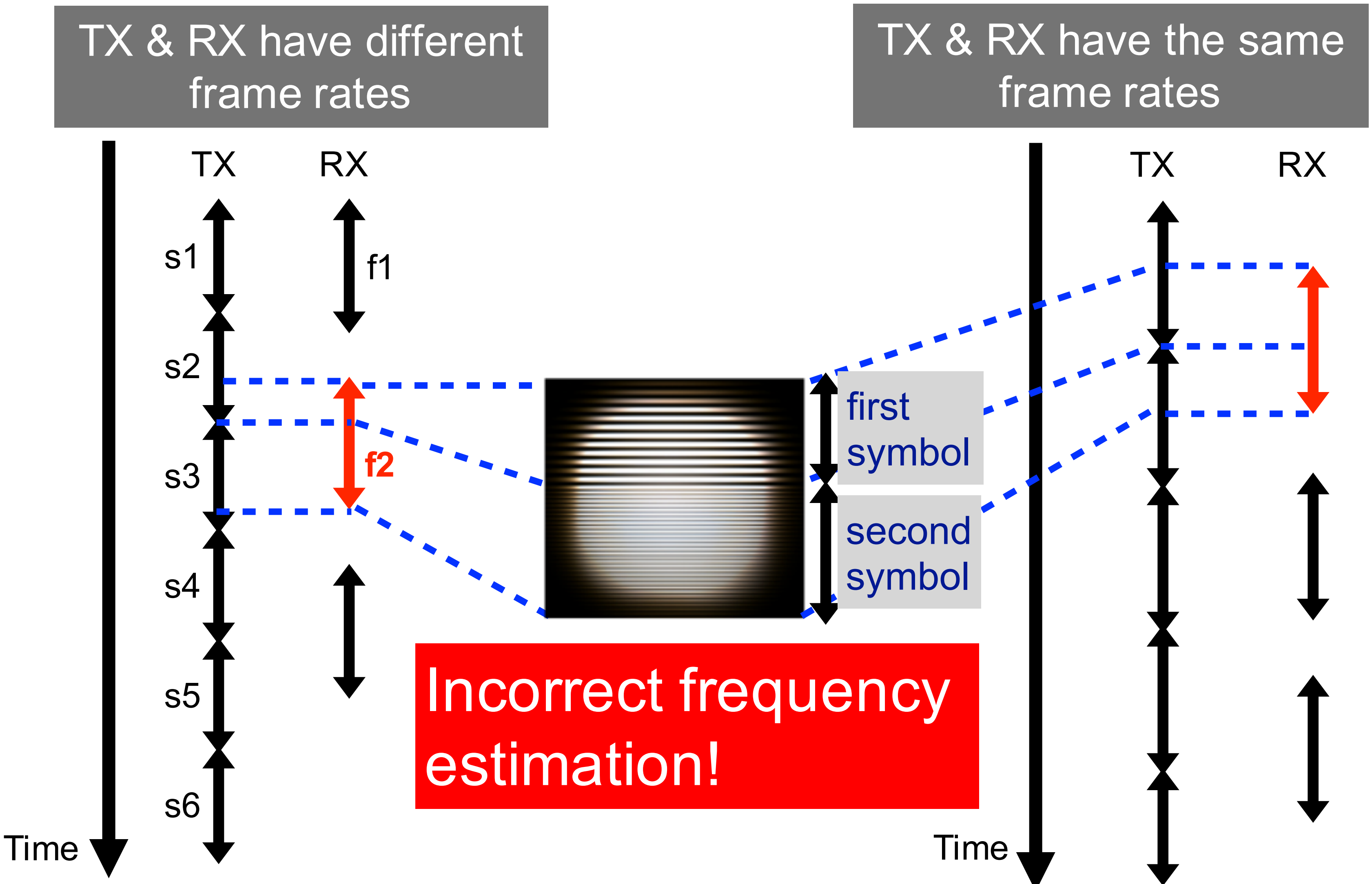
2. Lost symbol detection

   Embedded Sequence Number

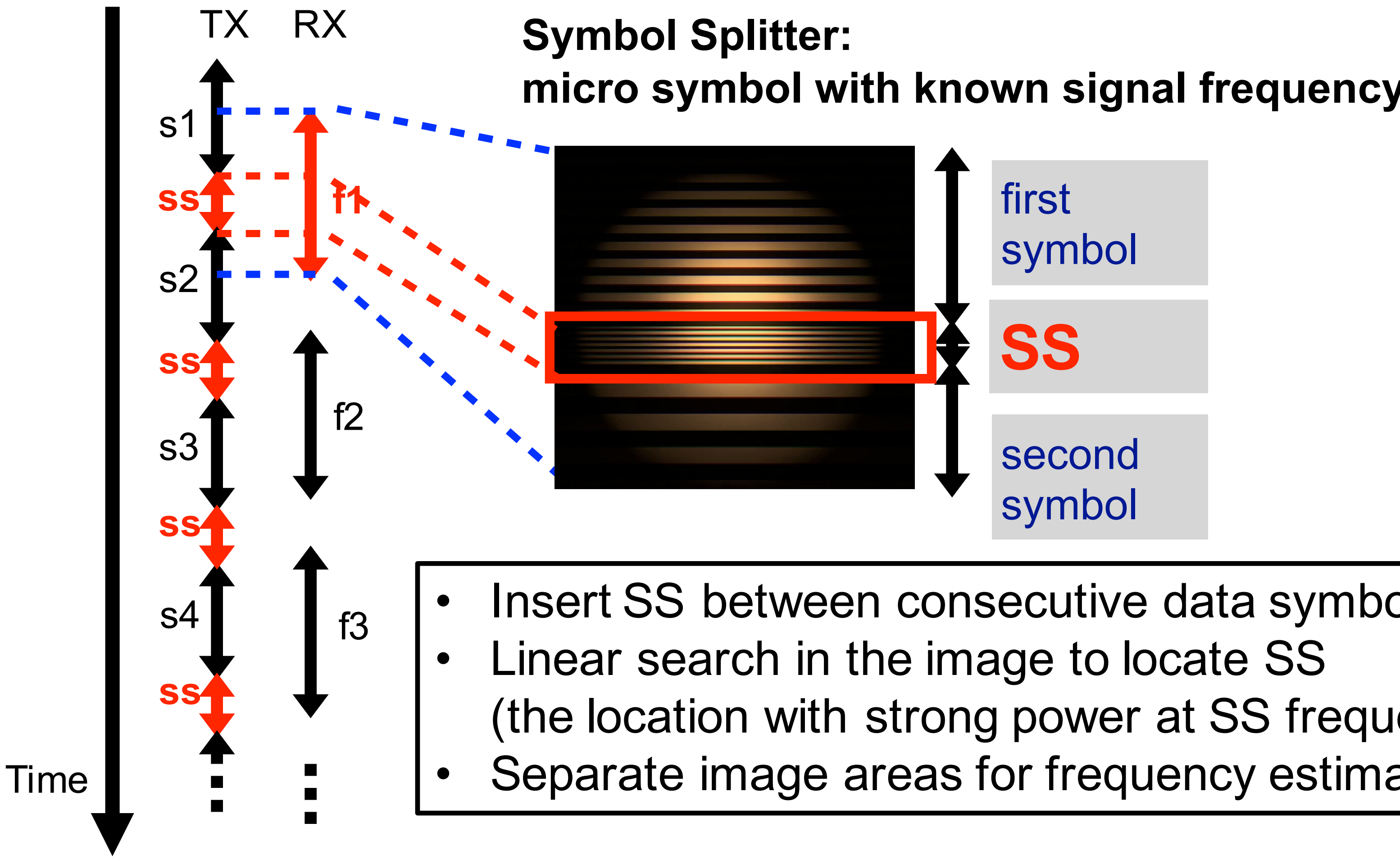
3. Recover from loss

   XOR-based Parity Code

1. Problem: Mixed-Symbol Frames



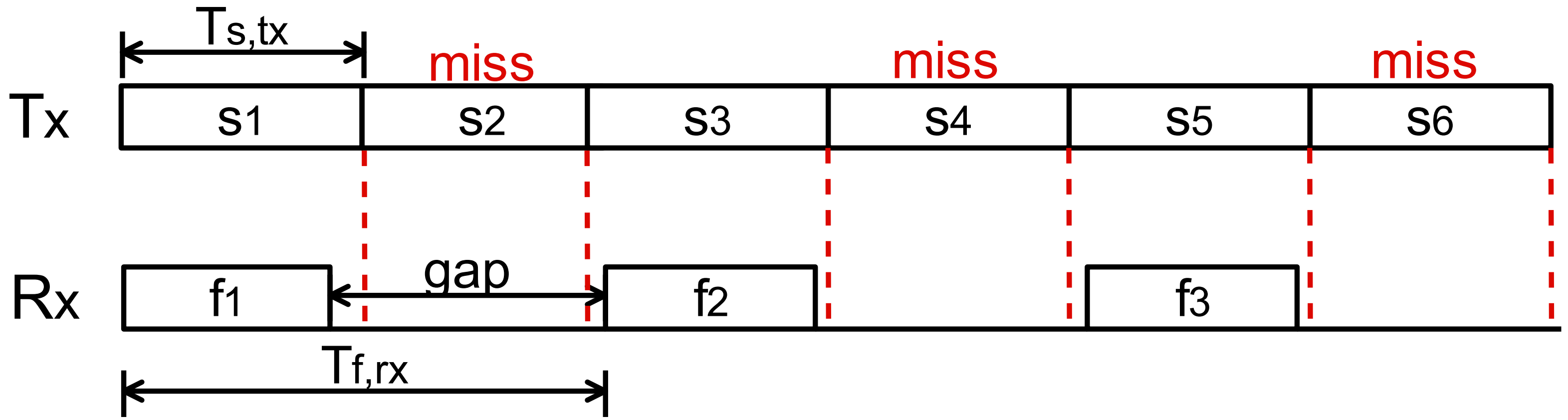
1. Solution: Symbol Splitter (SS)



- Insert SS between consecutive data symbols
- Linear search in the image to locate SS (the location with strong power at SS frequency)
- Separate image areas for frequency estimation

2. Problem: Lost Symbol Detection

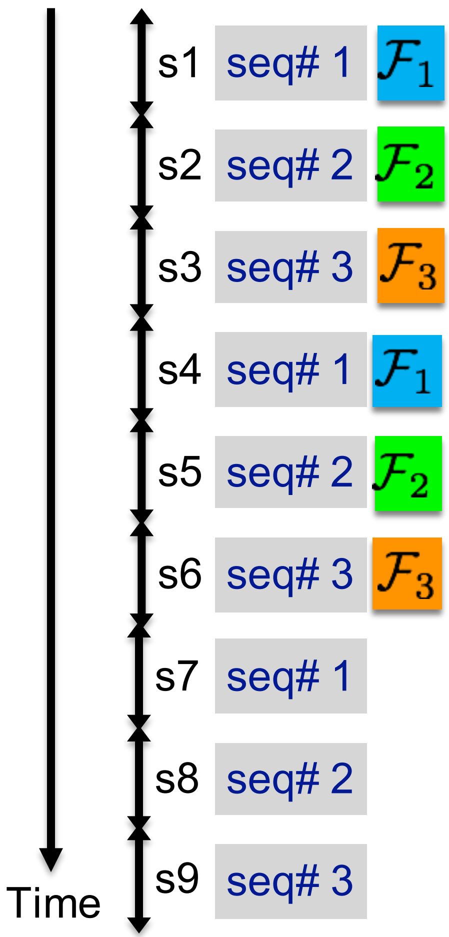
When TX frame duration $T_{\mathrm{s,tx}}$ < RX frame duration $T_{\mathrm{f,rx}}$



Entire symbol could be lost in the **gap**!

1. How does the receiver know a symbol is lost?
2. How to recover the lost data symbol?

2. Solution: Embedded Sequence Number



Assume no consecutive symbol losses*:

1 , 2 , ~~3~~ , 1 , 2 —> 3 is lost
1 , ~~2~~ , 3 , 1 , 2 —> 2 is lost
1 , 2 , 3 , ~~1~~ , 2 —> 1 is lost

3 sequence numbers needed

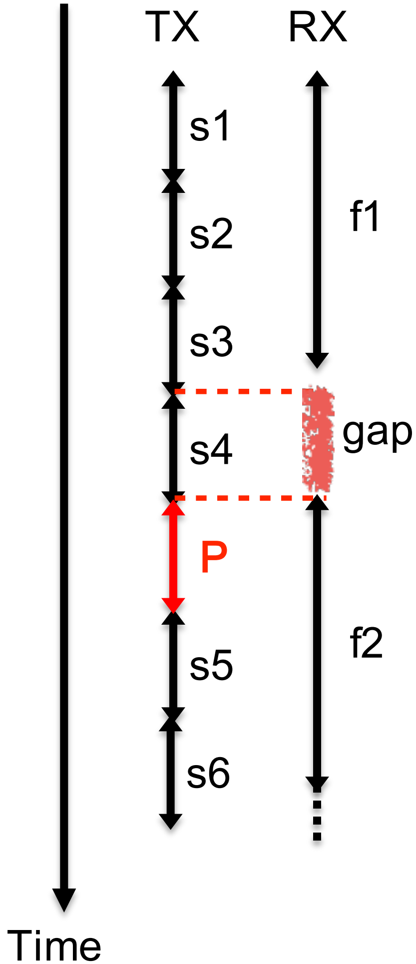
How to embed sequence numbers into symbols?

$$\mathcal{F} = \left\{ \left[f_1, f_2, \ldots, f_k, \right] \mathcal{F}_1 \; \left[f_{k+1}, f_{k+2}, \ldots, f_{2k}, \right] \mathcal{F}_2 \; \left[f_{2k+1}, f_{2k+2}, \ldots, f_{3k} \right] \mathcal{F}_3 \right\}$$

3 **sets of frequencies** to represent 3 sequence numbers

*This is true when the TX & RX frame rates are not different by more than 2 times

3. Solution: XOR-Based Parity Code



- Add parity symbol **P** every **N-1** data symbols
- Recover when 1 out of N symbol is lost

Determine N from loss probability:

$$P_{loss} = f(H, T_r, T_e, T_{f,rx}, T_{s,tx})$$

$$\Longrightarrow N = \frac{1}{P_{loss}}$$

Light size
Read-out duration
Exposure duration
Transmitted symbol duration
Receiving frame duration

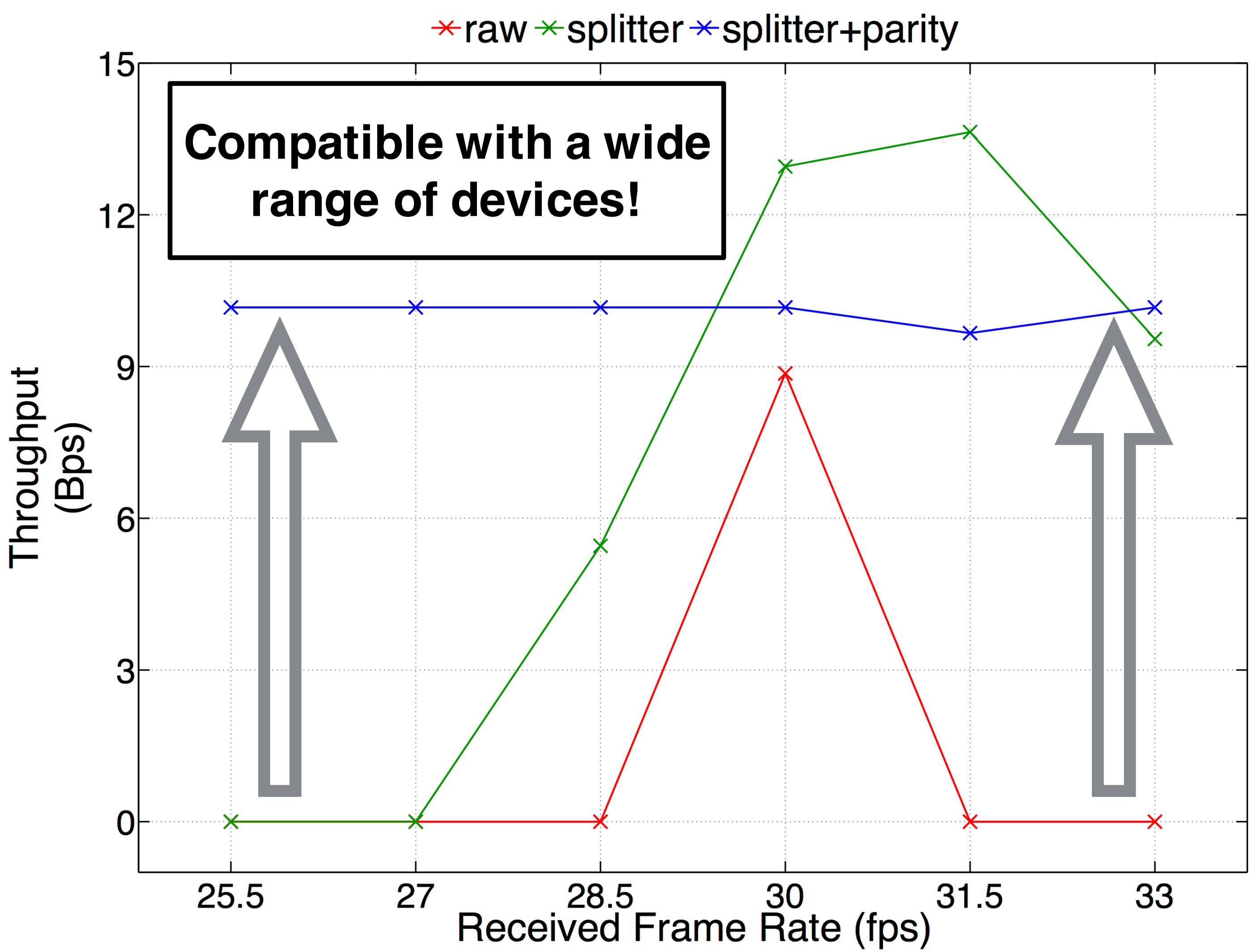
Derivation of Symbol Loss Probability

$$P_{\mathrm{loss}} = \max\left(\frac{T_{\mathrm{gap}} - T_{\mathrm{s,tx}}}{T_{\mathrm{f,rx}}}, 0\right)$$

$$= \max\left(\frac{T_{\mathrm{f,rx}} - (H-1)T_r - T_e - T_{\mathrm{s,tx}}}{T_{\mathrm{f,rx}}}, 0\right)$$

H : Light size (number of rows)
T_r : Read-out duration
T_e : Exposure duration
$T_{\mathrm{s,tx}}$: Transmitted symbol duration
$T_{\mathrm{f,rx}}$: Receiving frame duration

Validation with Experimental Results



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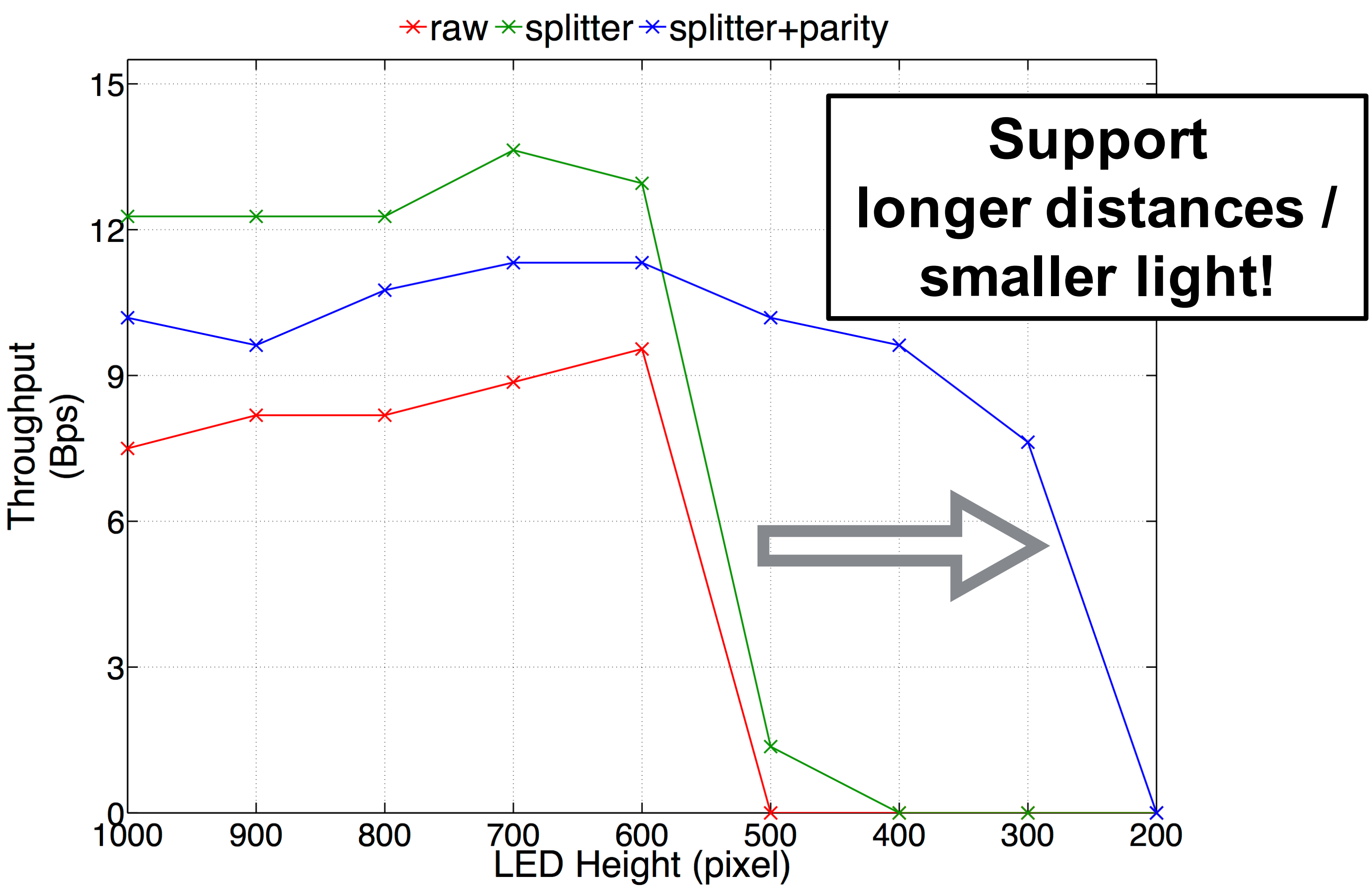

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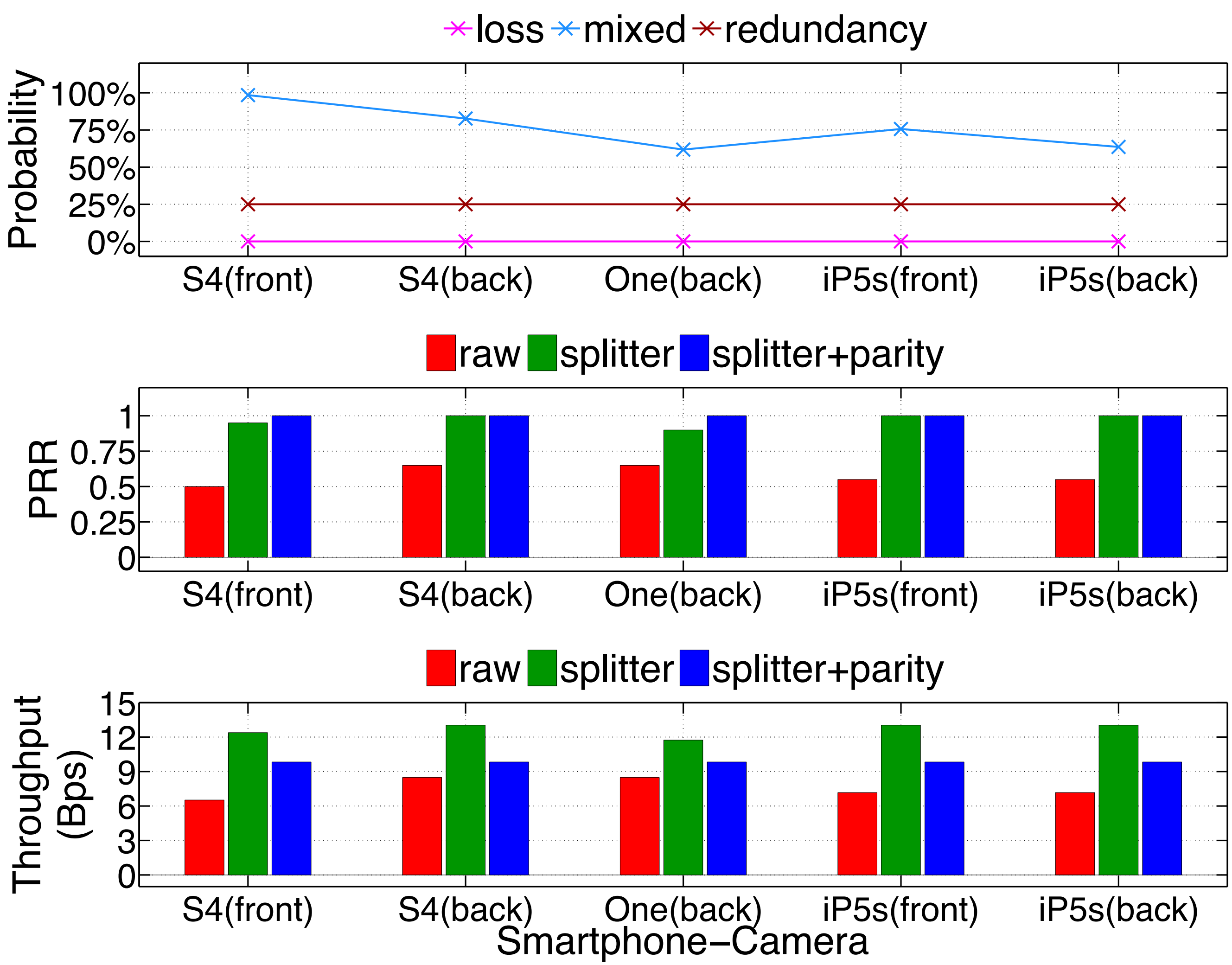
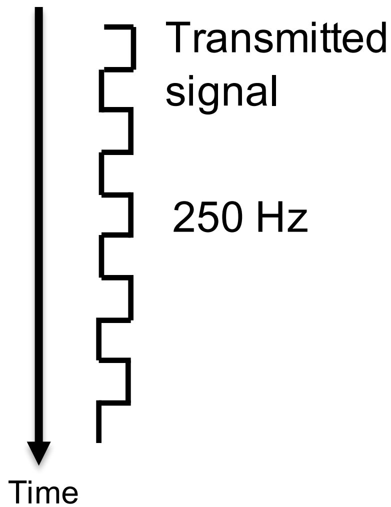
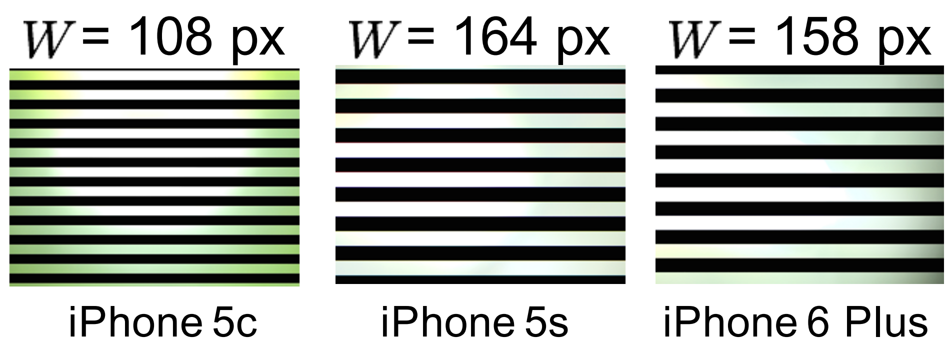


Preamble – Read-Out Duration Estimation

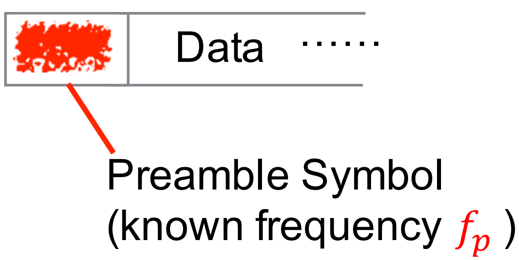
Channel Estimation - T_r





Different cameras have different T_r !

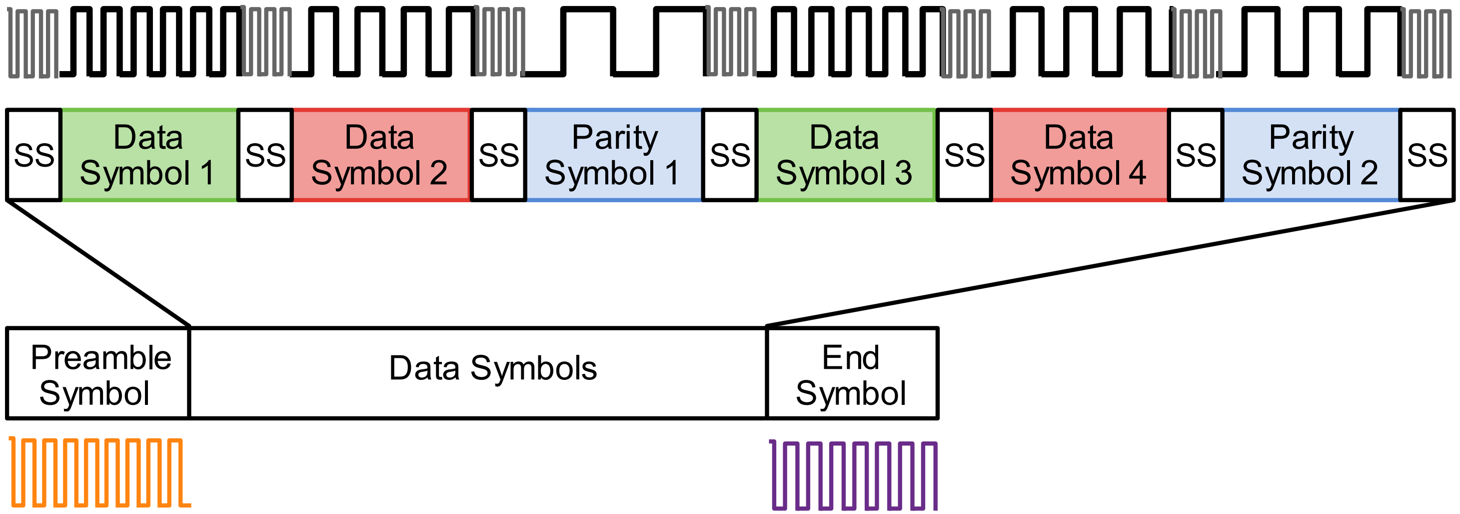
Packet format



Learn T_r from the preamble:

$$\Longrightarrow T_r = \frac{1}{2W f_p}$$

Proposed Frame Format



Additional frame header fields for open systems:

1. Selection of PHY data and SS frequencies (Number of frequencies used: 2 byte; Actual used frequency in Hz, 2 byte per frequency)
2. Parity density N (1 byte)
3. Checksum (optional, 2-4 bytes)